Production and Installation of Vertical Water-Wheel Generators

W. D. HOUSER
ASSOCIATE MEMBER AIEE

W. HINDLE
ASSOCIATE MEMBER AIEE

J. A. TYERMAN
NONMEMBER AIEE

Synopsis: This paper deals with the shop work on Canadian Westinghouse water-wheel generators and with their installation at various hydroelectric stations. The mechanical aspects of such machines are important to the erection as well as in the production operations. The tolerances called for are remarkably close considering the size and weight of the components and the fact that large machines are erected on site. The remarks on design are confined to those concerning components.

THE demand for power in all parts of Canada has doubled each decade since 1910. Mostly the increased load has been taken care of by building hydroelectric stations. The total installed hydroelectric capacity in Canada at September 1, 1954 was 16,000,000 horsepower. The characteristics of the equipment installed depended, of course, on the local conditions, which in no two places were exactly the same. Generators had to be built to suit and data are now available on a wide range of speeds and capacities.

Details of production and erection are described which in practice have been found to be advantageous in installing more than half of the water-wheel generators in Canada. The thrust bearing is the starting point for the mechanical engineer on a generator design and the construction of Kingsbury-type bearings will later be discussed at length. All work in the shops is, of course, planned so each component will be at the site when required by the erectors to meet the construction schedule. First to go are the foundation bolts and details which have to be placed while the forms for the concrete foundation are being built. These are followed by the frame and sole plates, spider and other rotor parts, shaft and thrust bearing, upper and lower brackets, and, finally, the exciters and air casing.

Formerly, the practice was to locate the sole plates individually. Instead, for a number of years past, considerable time has been saved by bolting the sole plates to the generator frame and allowing it to position them for location and elevation. A removable ferrule in the bolt assembly allows for the final centering of the stator. The foundation bolts are, of course, placed in pipe sleeves to permit horizontal adjustment of the sole plates. No paint is applied to surfaces coming in contact with the concrete as bare metal has better adherence.

Stator

The generator frames as now designed and constructed are the result of lengthy experience. Those used in the late 1900's were built up with sections of cast iron. They were superseded by frames of fabricated steel construction. Earlier designs were subject to warpage and cracks which required extra time to correct and added to erection costs.

Modern frames comprise a series of flat, annular, uniformly spaced rings behind the stator punchings. These rings are positioned by vertical plates, structural shapes, and pipe spacers. A steel cover wraps the rings, providing support and controlling the ventilating air. Additional web plates and rings are placed above the stator punchings to support the superstructure of the machine.

Accurate machining of the bore of the stator frame is essential for satisfactory stacking of the punchings; see Fig. 1 Bores are usually held to ± 0.005-inch diameter regardless of size. Out of roundness of the bore is held to similar accuracy. The over-all height of the frame is not usually critical; however, parallelism between the top and bottom face of the frame must be held to a tolerance of 0.016 inch.

High-grade silicon steel laminations are used in all large water-wheel-driven generators where efficiency is a consideration. This iron must be accurately punched so that it will build to the correct diameter with smooth faces and slots. Subsequent to punching, the iron is annealed and burr-ground to improve the electrical characteristics and it is coated with an adequate insulating material. Two coats of sodium silicate are used as it is one of the most permanent and fire resistant types of coating available. The fingers of the iron are supported by finger plates. To prevent vibration of the iron in the slot portion, it is essential that the finger plates provide adequate support to the iron. For this purpose the use of nonmagnetic rolled steel fingers held to a heavy steel punching by spot welding has been standardized. This construction provides the maximum mechanical reliability without increasing the core loss in the generator. Vent finger plates spaced at regular intervals in the stator core are of similar construction to the end plates except that the fingerlike spacers are a much smaller nonmagnetic steel section.

After the punchings are stacked in the frame and compressed or "pulled down," Fig. 2, the through bolts are welded to the frame, top and bottom and at each intermediate frame ring, to tie the iron core securely to the stator frame. The ends of the stator slots are dressed off to remove sharp edges which might damage the coil insulation during winding. Gauging of the slots assures that the coils will fit the slots. The stator bore is checked for roundness and dimensions to make certain that it is within the required tolerance. It is normal practice to allow the stator bore measurements to average from size on to $+0.030$ inch with a maximum variation from the average of ± 0.020 inch. However, other electrical considerations for the air-gap design often affect these tolerances.

Experience indicates one and sometimes two coil support rings are necessary to prevent movement of coil ends under short-circuit conditions. These must be accurately located so that the coil does not have to be distorted or pulled back excessively to come up against the rings. For this purpose, the rings are located by an accurate gauge which is positioned relative to the slot and has exactly the same kick as the coils. This procedure allows installing coils without undue straining which could shorten the coil life. Furthermore, coils are inspected for shape on a master gauge which assures that any spares will also fit the slots and support rings. Installation of coils or "winding" is shown in Fig. 3.

Coils and slot manufacturing tolerances are such that there is no possibility of having a tight coil that cannot be inserted in the slot. It is essential, however, that the final clearance be less than 10 mils to prevent vibration of the coil in the slot. This is accomplished by wedging

Paper 55-162, recommended by the AIEE Power Generation Committee and approved by the AIEE Committee on Technical Operations for presentation at the AIEE Winter General Meeting, New York, N.Y., January 31–February 4, 1955. Manuscript submitted October 18, 1954; made available for printing December 2, 1954.

W. D. HOUSER, W. HINDLE, and J. A. TYERMAN are with the Canadian Westinghouse Company, Ltd., Hamilton, Ont., Canada.

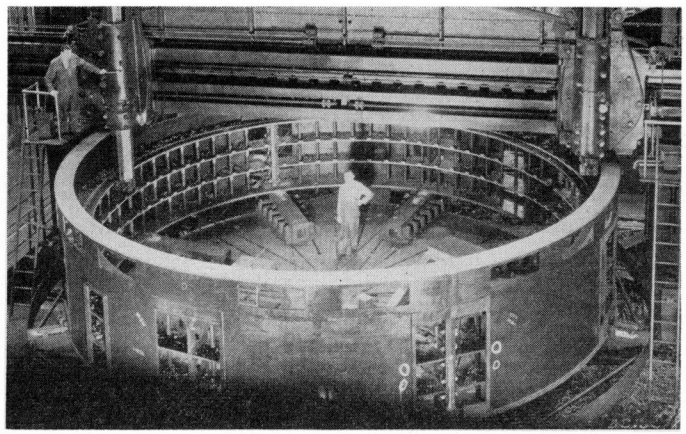

Fig. 1. 50,000-kva generator frame on a 36-foot horizontal boring mill. The openings around the frame are for mounting the air coolers

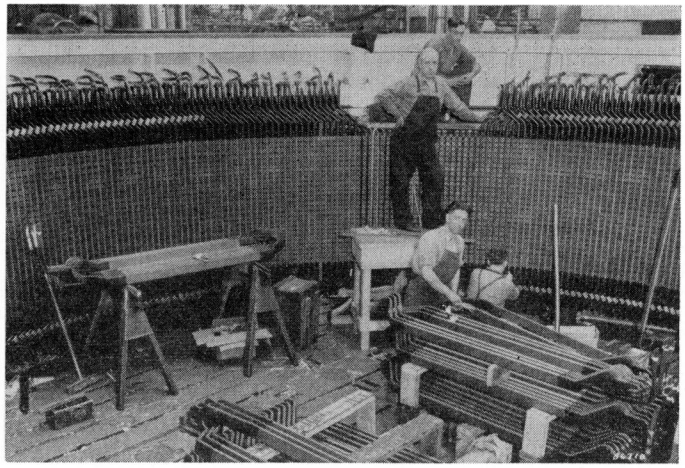

Fig. 3. Winding of the coils in the stator is one of the longest assembly operations whether in the shop, as shown, or in the field. The long leads projecting from the top of the coils eliminate individual group and series connectors

the side of the coil with a mica or a semiconducting plastic sheet. This sheet is supplied in a range of sizes from 0.010 to 0.025 inch to accommodate the tolerance range allowed.

Since 1942 it has been the practice of the Canadian Westinghouse Company to braze all connections on the armature winding including series, group, and parallel rings with a silver-phosphorus alloy. This procedure eliminates the uncertainty of soldered connections and reduces the number of connections by one-half. Slot wedges are made from cloth-base micarta strips principally because of their strength, uniformity, and dimensional stability. These wedges are notched opposite the ventilating ducts to facilitate a streamline flow of air through the duct. Depending on customer preference, the stator may be either stacked and wound in sections, in the factory, or in a complete circle in the field. In many cases it is preferable to stack and wind in the factory to reduce the assembly time and the usual congestion in the powerhouse.

In the event that the stator arrives on the job in stacked and wound sections, it is set up to correct elevation and centered, sole plates are grouted and the coils bridging the splits between sections are made up to complete the winding. This is a time when great care must be taken as stator winding should only be attempted by experienced workmen under expert supervision. The winding personnel are supplied with special rubber mallets, wedge drivers, side-mica drivers, and pullers as well as all the necessary winding information from the design engineers. Where coils are to be heated during winding (continuous taped asphalt bonded type), brazing transformers with special connectors are available.

The number of coils lifted during the closing of a split depends on a number of factors and should be determined for each particular winding. Some of the factors involved are:

1. Type of coil, i.e., mica folium, continuous taped asphalt bonded, or Thermalastic.
2. Depth of slots.
3. Throw of coils.
4. Frame size.
5. Voltage class.

The number may vary from three to six times the number of coils in the throw. The risk of possible coil damage is great if less than the recommended number of coils are lifted while a larger lift than necessary results in increased cost, time, and disturbed coils. After the coils are placed in the slots and before connecting, they are given a momentary high-potential test 1.25 times final test voltage. After connection, and before the rotor is placed in the stator, the winding is given a momentary high potential of 1.15 times final test voltage. These potential tests may be made with either alternating voltage, or the equivalent direct voltage. Each coil is tightened in its slot, as mentioned previously, based on individual measurement. Contact resistance tests with an ohmmeter check this operation.

When the complete stacking and winding is to be done at the site, the frame is set up, if possible, in its final location on the generator foundations with stacking and winding operations being carried out in position. On occasion it may be necessary to stack and wind in the erection bay, in which case the complete wound and stacked stator is moved as a unit to the generator foundations and is set to correct elevation and centered. To provide additional strength, on conventional machines, the upper bracket is usually mounted temporarily on the stator before the lift is made.

The elevations and center may be set by the turbine-shaft coupling location,

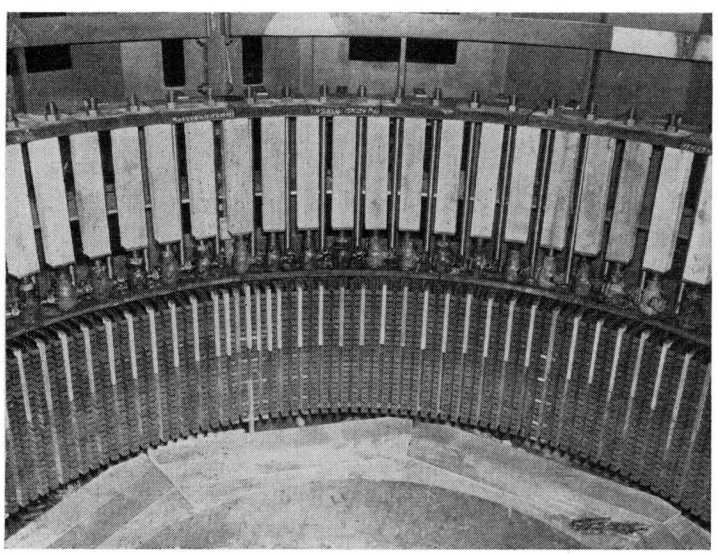

Fig. 2. Partially stacked 106,000-kva frame showing the pressing operation which is carried out for every 12 inches of iron added. The 25-ton jacks bear down on temporary pressing plates. The stator tie bolts are visible between the jacks; guide strips maintain slot alignment

when available. A piano wire plumb line with a 100-pound lead weight damped in a pail of heavy oil is suspended from the top of the stator frame. Its exact location is determined either from permanent reference plugs set in the foundations or from the turbine-shaft center. The stator frames are centered to ±0.032 inch and to level within 0.004 inch. Engineer levels, micrometer targets, and pin gauges are used. The stator is now dowelled to the sole plates.

Rotor

The rotor transmits the torque from the shaft to the field poles and consists of a spider, rim, poles, blowers, and other miscellaneous parts. The rotors fall into two general classifications:

1. Umbrella design; see Fig. 4(A).
2. Conventional design; see Fig. 4(B).

The umbrella design is usually applicable to large-diameter slow-speed machines, while the conventional design is usually confined to high-speed generators. The umbrella design provides manufacturing economies as well as reduced installation costs at the powerhouse. The rotor can be lifted separately from the shaft; see Fig. 5. Thus crane capacity is reduced by the weight of the shaft, which in the case illustrated amounted to 10 per cent of the weight of the rotor. An umbrella installation also reduces the powerhouse building costs by lowering the crane rail height required for dismantling a generator.

The bearing support bracket for the umbrella-type unit is less expensive than the supporting bracket for conventional units. Since the span of the bracket is reduced and since the stator frame does not have to support any vertical thrust from the rotor, there are further design economies.

Today spiders are either fabricated or built up of disks of plate steel. For fabricated spiders, generally only the hub section is built up from annular rings of heavy plate steel. Arms of I-beam or box sections are welded to the hub. At the ends of the arms there is a heavy post to take the "shrink" and "torque" keys, which hold the rim on the spider. After fabrication, this section is stress-relieved to assure that the dimensional accuracy of the machine will be maintained and to eliminate any danger of operating failure from residual stresses. The spider is machined on a boring mill to tolerances of 0.003 inch on the bore and 0.005 inch on the arms.

In designs where it is impossible to use the laminated rim construction because of small diameters or high centrifugal forces, the plate type of rotor is used. A noninterconnected stack of completely machined disks is used. These disks are shrunk on the shaft as an accurately machined assembly. The poles are attached directly to the plates by dovetail slots in the outer edges.

The fabricated spider involves an outer rim. The function of this rim is to contain the centrifugal force of the poles during operation and to provide a flux path between poles. A staggered assembly of sheet steel segments is used. These segments act as a link structure so that the segments are in tension with the forces transmitted to the next segment by means of the through bolts acting as shear pins. Consequently, no reliance is placed on frictional forces to hold the rim punchings when rotating.

The rim punchings must build up in a circle of sufficient accuracy to have no appreciable affect on the air gap. This frequently requires an accuracy in the rim punching segment to within 0.002 inch. Such accuracy is achieved by a compound die without any resort to indexing and its resultant inaccuracies.

In building the rim, Fig. 6, the lower end plates are set up in correct location on the spider and are supported from the floor. Temporary building keys are

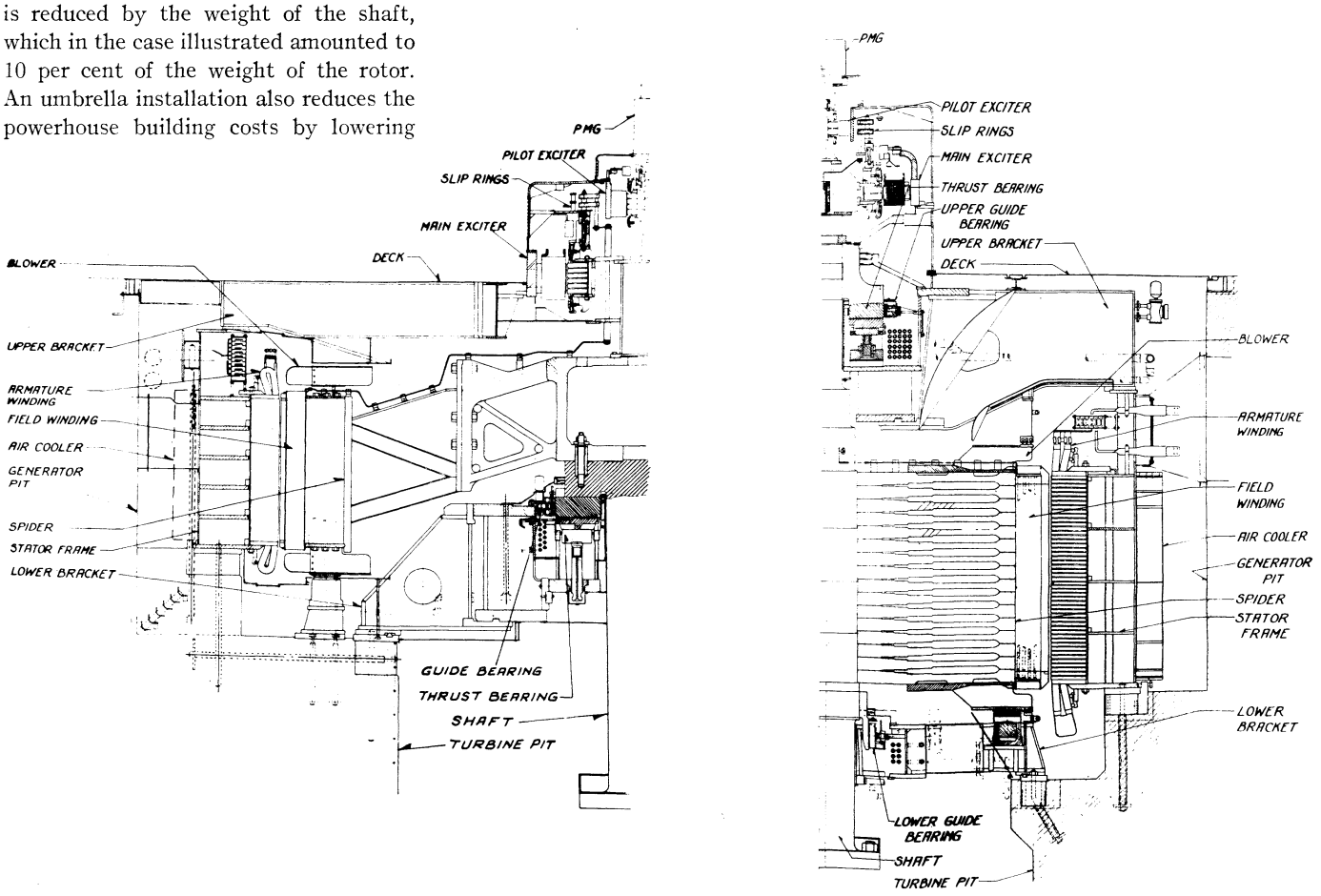

Fig. 4. (A)—Type of spider and bearing inherent in umbrella-type machines. (B)—Application of plate spiders in conventional-type machines

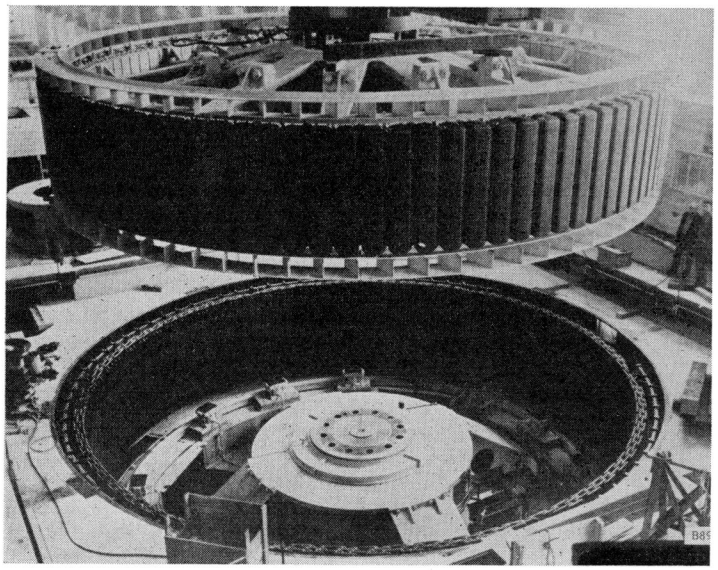

Fig. 5. The umbrella - type rotor shown ready for lowering into the stator is complete with rim and field poles, top and bottom blowers. Already installed in the lower bracket are the thrust bearing and shaft. Also visible are the hydraulic brakes sitting on the bracket arms

placed in the spider arm dovetails. As the laminations may vary slightly in thickness within the tolerances of the steel suppliers, every effort is taken to ensure proper distribution of each box of punchings so that the rim thickness will build up evenly. Stacking is carried out with the aid of accurately machined building pins. The laminations are pressed after every section of approximately 12 inches has been stacked. These methods ensure a tight, compact rim of accurate diameter. Permanent rim studs are inserted and tightened to a predetermined tension.

After the rim has been stacked the temporary dovetail keys are removed and the rim is heated by electric space heaters for the insertion of the permanent torque keys. The amount of interference is such that at moderate overspeed the rim remains tight on the spider but, at maximum overspeed, the centrifugal forces overcome the interference forces. Before the rim has cooled, the permanent rim stud nuts are checked for tightness with a torque wrench to ensure that all studs are under the correct tension. When cool, the nuts are welded top and bottom.

The field poles carry the magnetic flux generated by the field coils and mechanically position the field coils. These poles are made up of sheet steel laminations, clamped together by end plates, and riveted together. Between the pole body and the rim is a dovetail joint designed to withstand the stresses at overspeeds and to prevent any relative movement of punchings. The poles are wedged tight into the rim by the tapered dovetail keys. These poles can be easily removed, if necessary for maintenance, by removing the dovetail keys with a special puller. For ease in fitting, the dovetail keys are tinned all over and hardened on each end for driving.

First the poles alone are tried and the dovetail keys are inserted and marked. The field coils are then slipped on to the poles and these assemblies are mounted. Considerable care is taken to ensure that the field coils are tight. The pole and coil assemblies are individually weighed before shipment to facilitate weight distribution around the rotor as this minimizes balancing problems.

Shaft

The generator shaft functions to transmit the torque from the water wheel to the rotor and to support the rotating members. This shaft is made from a carbon steel forging which has been heat-treated to make a homogeneous metallurgical structure free from forging and casting stresses. It is turned and polished all over to reduce stress concentration to a minimum. Essential areas such as come in contact with other members are accurately machined and ground to ensure the satisfactory alignment of the unit. Shafts of this nature are liberally proportioned so that stresses are low and conditions of critical speeds and magnetic pull are satisfied.

The thrust collar is a continuous part of the shaft forging for umbrella-type machines; see Fig. 7. On conventional units, when a separate thrust collar is required, the collar is assembled with a light interference fit to assure accuracy of alignment and to prevent movement and fretting corrosion. The outside diameter of the thrust collar face is machined to runout of less than 0.0002 inch. The runout on the ground surfaces is also held to 0.0005 inch.

For a conventional unit the shaft is positioned vertically through the floor opening in the erecting bay of the powerhouse and is blocked at a suitable eleva-

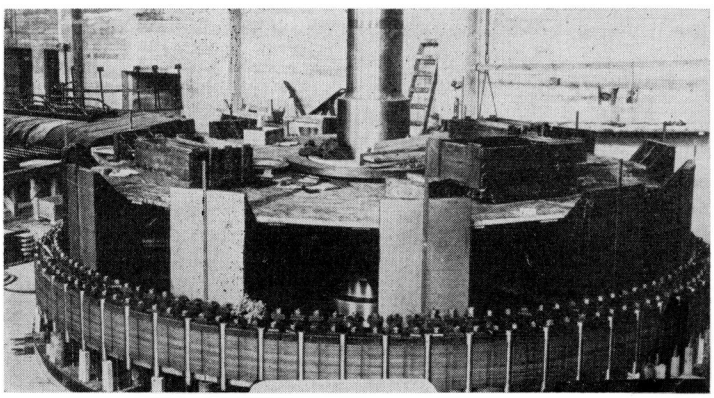

Fig. 6. Stacking rim punching. This rotor spider is shown with the rim punchings partially stacked. The pins or rods used for maintaining alignment of the dovetail slots are self-evident around the outside edge. The temporary pressing bolts shown are removed when the next pack of punchings is added

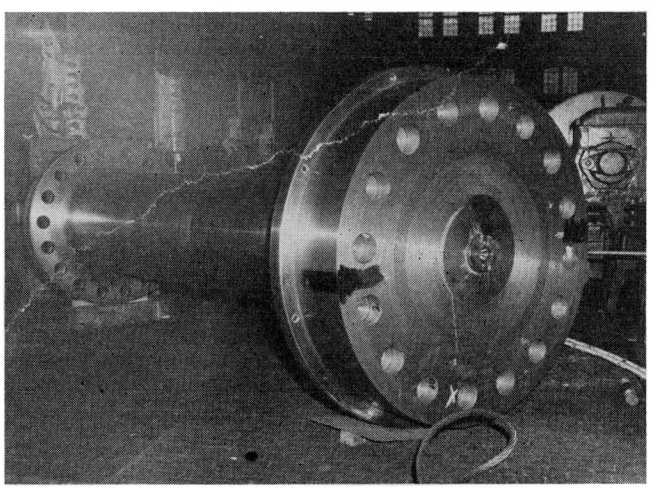

Fig. 7. All flanges on this shaft for an umbrella-type machine are an integral part of the forging. The large flange at the top end is for bolting to the underside of the rotor

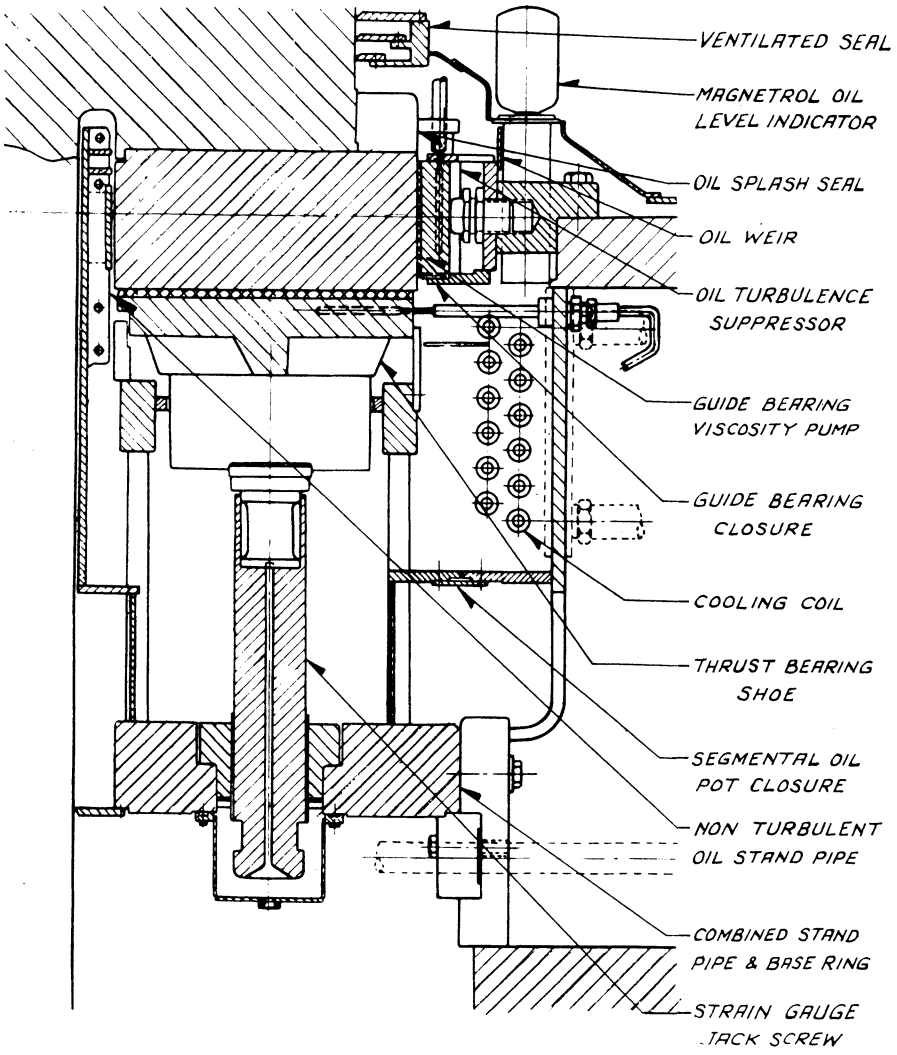

Fig. 8. Combined thrust and guide bearing assembly for umbrella-type machines, Kingsbury-type bearing

tion. The shaft at the spider fit and the hub bore of the spider are cleaned and checked for burrs or other imperfections and the fit dimensions are carefully measured as a check on the interference provided. The hub is expanded by use of space heaters to a predetermined clearance of the bore. The hub bore and shaft fits are brushed with light machine oil or a solution of molydenum disulphide and the hub is lowered down over the shaft with the use of the powerhouse crane until it is correctly positioned with the bottom against the shoulder on the shaft. Accelerated cooling on the bottom of the hub contracts this part of the hub on to the shaft first and prevents the spider from pulling away from the shoulder as it cools.

On occasion, the hub may be expanded while in a position around the shaft above the fit, with the shaft being pulled up by the crane to the correct location. This method is used where the spider is of the plate type. The shaft-lifting device provided must be suitable for lifting the total weight of shaft and spider. With the umbrella-type rotor it is not necessary to stack the rim over a pit as the shaft is not connected to the spider during this operation. Hence, the spider may be set up anywhere in the powerhouse where suitable space and permissible floor loading is available.

Brackets

The function of the main bracket is to support the weight of the rotating members through the thrust bearing and maintain alignment through the guide bearings mounted thereon. The bracket consists of a fabricated hub section which serves as the oil pot and bearing support. This hub is usually supported by four to eight radial arms which transmit the forces to the foundations. The deflection of these brackets under load must be held within limits which will assure clearances in water-wheel parts and exciters in the order of 0.10 inch.

All oil tight welds are designed with welds on both sides, each of which are checked for oil tightness. After fabrication the bracket parts are stress-relieved by heat treatment. The lower bracket is assembled in the erecting bay, placed in position and accurately centered within ± 0.010 inch, and leveled to within 0.0005 inch per foot of span. Dowelling to the grouted lower bracket sole plates completes this operation. The upper bracket is centered and leveled to similar accuracy and dowelled in position to the frame prior to final assembly and then removed until the rotor is in place.

Thrust and Guide Bearing

As stated previously, the thrust bearing is the heart of the mechanical design. The Kingsbury-type bearing design, Figs. 8 and 9, has been further refined since 1948 because of new babbitting techniques, improved oil cooling and circulation, improved manufacturing practices, and metallurgical developments. The modern bearing is simple to install and adjust, reliable in service, and easy to maintain.

Bonding of babbitt to the individual bearing shoes has struck a serious obstacle in the blistering of the babbitt face by hydrogen released from the steel shoe. To circumvent this hazard, the "no bond" practice has been adopted where the babbitt is held mechanically to the steel by a network of dovetail slots. Operating experience is now proving this practice sound.

A viscosity pump designed into the trailing edge of the thrust bearing provides a unique improvement in the oil circulation. This arrangement gathers the hot oil from the trailing edge and discharges it directly into the area of the finned copper cooling coil. Without it, hot oil is picked up by the next shoe. This viscosity pump along with carefully placed baffles and liberal passages have all improved the circulation within the bearing oil pot. Foaming from turbulence at the top of the oil pot is controlled by a baffle and weir construction in conjunction with a viscosity pump built into the guide bearing; see Fig. 8. Air in the bearing oil film means increased kilowatt losses and higher bearing temperatures.

The runner plate is made from gray cast iron with chilled rubbing faces. Addition of nickel in the iron results in a close grain structure that can be lapped to a high polish. The oil absorbed in the microscopic pores of the cast iron and the flake graphite in the iron act as a solid lubricant in starting, prior to the establishment of the oil film.

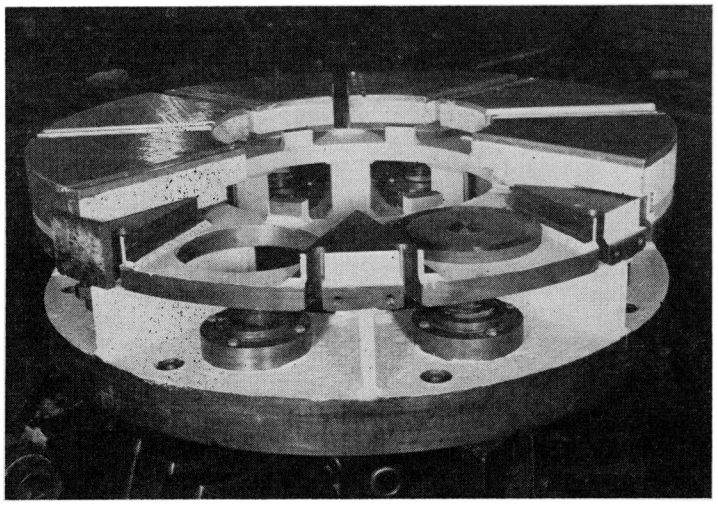

Fig. 9 (above). A 56-inch thrust bearing with two shoes and one jack screw and shoe support removed

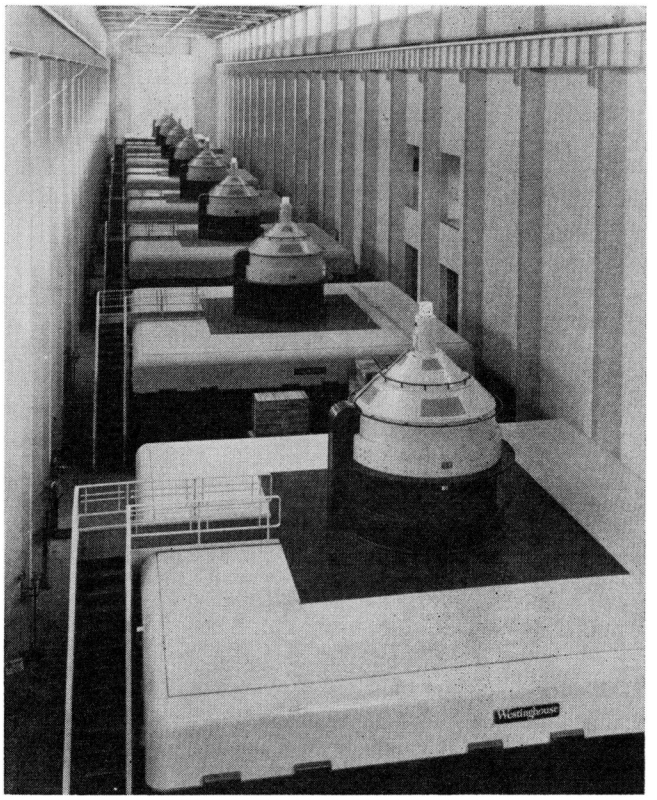

Fig. 10 (right). Des Joachims Generating Station on the Ottawa River consisting of eight 50,000-kva 106-rpm conventional-type generators with cooling air recirculated through air-to-water coolers mounted on the frame

For the thrust bearing to give the most efficient and satisfactory service, it is imperative that the utmost care is taken in the cleaning and handling of the components during installation. The assembly must be done under proper working conditions in a clean atmosphere free from abrasive dust or dirt.

With the rotor placed in position, supported by the brakes, the upper bracket is installed and the thrust bearing base ring complete with jack screws and shoe supports already assembled is placed in its proper location in the oil pot. The bearing shoes are assembled on the shoe supports and lightly brushed with a graphite grease after which the runner plate is placed on the shoes. The thrust collar is pressed on the shaft using a pressing plate and pressing bolts. The fits are lightly coated with molybdenum disulphide to prevent galling. The circular key is inserted and the runner plate is fastened to the thrust collar. Proper load adjustment on the shoes and jack screws is now obtained through the use of strain gauges permanently located in the jack screws; these gauges may usually be adjusted within $\pm 2^1/_2$ per cent. For machines ordered without strain gauges, the "slugging arc" or other methods are used for adjusting the load.

The modern guide bearing has multiple, individual shoes. Separate adjustment on each shoe makes alignment easier and more accurate than with the ring-type guide bearing. Maintenance or replacement is simplified and bearing losses lowered. The individual shoe is generally set for a clearance of 0.010 inch from the journal, which is ample allowance for thermal expansion. It is usually possible to combine one guide bearing into the thrust bearing assembly. Here the periphery of the runner plate acts as the journal for the guide bearing.

Exciters

For the last number of years, direct connected exciters have been specified. One effective manner of reducing the over-all height was to use a telescopic construction in which the pilot exciter is located partially within the main exciter commutator. The armature winding of the exciter is electrically balanced to reduce the effect of unbalanced magnetic pull.

Exciters are tested in the shop where brush neutral, compensation, etc., are set to eliminate field adjustments. New designs are given a heat run and all designs are checked for ability to meet the specifications. Until recently the exciter system has taken the form of main and pilot exciters. In cases where the magnetic amplifier type of voltage regulator is specified, the direct connected pilot exciter is entirely eliminated.

General Features

Most users today prefer an enclosed ventilation system. Centrifugal blowers mounted on the rotor force the air through the core of the machine and through the air-to-water coolers on totally enclosed generators. All air passages in the machine have been improved to increase the air circulation and, in recent years, this has included new stator wedge and new vent duct designs. Air turns and splitters are put in at advantageous points to direct the air with a minimum drop in pressure. To eliminate hot spots, air coolers are arranged around the frame of the generator. These coolers are designed so that there is no possibility of air locks in the water tubes which in the past have caused considerable loss in cooling capacity.

The spider of an umbrella-type generator is connected to the top of the shaft with a circle of hollow dowels which have a light interference fit in both shaft and spider. Bolts inside the hollow dowel hold the assembly together. During assembly these dowel holes are reamed after the rotor is lowered onto the shaft. At this time, the weight of the rotor is actually carried on the brakes, with the safety blocks in place. Suitable fixtures are supplied for the rapid insertion or the removal of these dowels. It is possible to have such a rotor out for repair 4 hours after the generator is shut down.

In the umbrella machine the unit is provided with a thrust bearing lowering device. The device consists of three power-driven screws, the running nuts of which attach to and lower the thrust bearing assembly. In the lowered position, all parts are accessible for inspection

and parts can be removed with a trolley supplied with the unit. On umbrella units designed for outdoor service, it is possible to remove armature coils and field poles for maintenance without opening the air casing or using overhead cranes. The field poles are removed by means of a monorail and chain block. Keys in the field pole dovetails are removed by means of a special puller.

The generator field circuit breaker is now often mounted on the upper bracket in close proximity to the exciter. This saves considerably in installation costs and dismantling of a unit as it is not necessary to disconnect heavy current-carrying field leads. The upper bracket, field circuit breaker, and exciter frames come off as a unit.

Alignment

In the umbrella installation the alignment is simplified because of the elimination of one of the guide bearings. In general, the shaft lengths are shorter which results in less throw because of the manufacturing tolerances necessary. The guide bearing located with the thrust bearing is adjustable to allow for final alignment later.

To retain permanent alignment records, it is becoming more common to work from permanent reference plugs, which are inserted while the concrete foundation is being placed. Once the shaft is in position, it is necessary to work from either the turbine shaft or the pit wall reference plugs. For alignment purposes, the generator shaft must hang freely from the thrust bearing, with the lower guide bearing left out.

The generator shaft coupling is located vertically at an elevation slightly below operating position, as it is important that any adjustment of the thrust bearing jack screws be done in a load-increasing, or upward, direction. Preliminary shaft alignment is carried out by adjustment of bearing jack screws until the coupling flanges are parallel within 0.15 mil and the flanges are in the same vertical plane.

Several upper guide bearing shoes are now tightened to prevent horizontal movement of the rotor. The rotor is rotated 360 degrees to distribute evenly the lubricant between the shoes and runner plate. The coupling flanges and the upper guide bearing journal are checked and the readings recorded. The rotor is then rotated 180, 360, and 540 degrees, with readings being checked and recorded at each position.

The shaft runout at the coupling flange should not exceed 0.00025 inch per foot of shaft from runner plate to coupling, and the out-of-parallelism between coupling flanges should not exceed 0.00003 inch per inch of coupling flange diameter at every check position. The guide bearing shoes are now removed and the final alignment and load adjustments are made. The coupling is now made up and the whole rotating assembly is checked. Once the alignment has been approved, final assembly to running clearances of the guide bearings is carried out. All bearings must be cleaned and flushed out to remove all possible foreign matter.

Dryout

The dryout of the windings depends on the insulation resistance readings, type of coil, and the urgency of the work. It is considered that, if the unit is urgently required for production of power, dryout may be omitted if stator winding insulation resistance to ground, per phase, is in the order of 75 to 100 megohms. However, if time permits, it is always good insurance to carry out the dryout until resistance readings become consistent for 48 hours, at a constant or corrected ambient temperature. A running dryout with stator windings short-circuited, is recommended.

The temperature should be brought up gradually but not in excess of 80 degrees centigrade, as measured by stator coil temperature detectors. Megger readings per phase should be taken at regular intervals and plotted on a graph. After the winding is dry, the generator may be given the final overpotential test, either a-c or d-c, at AIEE test standards[1] and placed on load.

Balancing

Although every precaution is taken in design, fabrication, and assembly to distribute the weight properly, once the machine is started up dynamic unbalance may be present. On higher speed machines, over 150 rpm, considerable success has been obtained by use of a portable dynamic balancer.

The low-speed machines are balanced by adding the necessary weight or weights by the vector analysis method, assisted by dial indicators. The shaft is painted with a thin coat of white wash in an accessible location near each guide bearing. Thousandths dial indicators are mounted to indicate the shaft at these spots. The unit is given an initial run and the throw is marked on the whitewash with a lead pencil or scribe. The indicator variations are recorded. On stopping, the high point of the throw is recorded in degrees from a reference plane. A trial weight is then applied at random and the trial run made and recorded. By vector analysis the initial unbalance is calculated and subsequently corrected by a balance weight placed directly opposite. The balancing operation may be repeated to refine the balance. On occasion, this procedure may require expanding into 2-plane balancing when dynamic unbalance is present.

General Remarks on Field Installation

Erection in the field is a continuation of factory manufacture and assembly. The large size of the machines prevents shipment as a completed unit. Engineering design and factory operations aim at reducing field work where possible, because limitations in facilities at the job site are the rule rather than the exception.

For economical and efficient erection a number of factors must be considered for each particular installation:

1. Delivery schedule of component parts: a proper sequence of shipment must be followed.

2. Manpower available: a basic crew of skilled workmen and supervisors with sufficient helpers is required.

3. Powerhouse conditions: sufficient working and storage areas are desirable as congestion makes for an inefficient operation. Cranes, compressed air, and construction power must also be available as required.

4. Overtime and shift work, while reducing erecting time, do not do so in direct ratio because of loss in efficiency. Realistic in-service dates should be laid down, as a month extra at the installation time may well result in months or years of extra life from the machine.

5. Erection equipment supplies must be adequate both from efficiency and safety standpoints, and must be of sufficient quantity for the job at hand.

Conclusion

It is safe to say that present-day designs for hydroelectric generators are a combination of improvements aimed solely at better output performance and at overcoming former operating inconveniences as well as facilitating assembly and maintenance. These latter improvements are almost entirely mechanical and are the natural outcome of years of experience on the part of both the design engineers and the operating engineers and personnel. Accurate manufacturing to close tolerances make the components for 400-ton generators as completely inter-

changeable as those for a washing machine motor.

The operators of expensive pieces of apparatus such as water-wheel generators are not backward in advising the manufacturer of what they consider shortcomings in any particular generator. If the shortcoming cannot be corrected in the generator in question, then at least the designer must overcome it in future designs.

As "down time" for maintenance often means a loss of potential revenue to the operator, generators that remain trouble-free mechanically save significant money each year. However, it is certain that no operator today would order a water-wheel generator expecting never to have to dismantle it for overhaul. Therefore, it is a further saving to this operator if he know that when such an overhaul comes up his machine will come apart and be able to be reassembled easily and accurately. These are goals towards which the design engineer and shop workman strive continually. No one would be satisfied today with a new machine built to 1930 design standards. Greatly improved designs are available today in generators, and more rigid and exacting purchase specifications are an indication that operators are well aware of the type of machine that is now available. The generator designer continually strives not only to keep abreast but to keep ahead of the buyers' specifications, and will be likely to continue to do so as long as we remain under the free enterprise system.

Reference

1. Test Code for Synchronous Machines. *AIEE Standard No. 503*, June 1945.

Discussion

F. H. Duffy (Aluminum Company of Canada, Ltd., Shipshaw, Que., Canada): The authors have done an excellent job of outlining the design and erection procedures of one manufacturer. It would be most interesting to hear from other manufacturers as to whether the same procedures are used.

One cannot help but be impressed with the close design tolerances maintained. In the industry it is often taken for granted, but the watchmaker type of work required is certainly worthy of emphasis.

Where direct current is used for test purposes it is assumed that the AIEE recommended ratio[1] is used.

Some elaboration on the use of the strain gauges for thrust bearing adjustments and the method of computing the $2^1/_2$-per-cent error in adjustment would certainly be of interest to operating personnel. When speaking of ease of assembly and fit of spare parts, it should be noted that any time the machine is dismantled or when there is a thrust bearing failure the same adjustment procedure must be followed. It might also be noted that in the erection of the unit, the trueness of the water-wheel erection has a definite effect on the ease of alignment.

Since the generator winding has been tested with high voltage and since short-circuit dryout uses about full load current, it would certainly seem more efficacious to eliminate the dryout period and generate useful kilowatt-hours by operating at slightly reduced voltage and load for the ordinary dryout time. It is probable that dielectric absorption tests are more indicative of the winding condition than any number of megger readings and these tests are easily made if a fairly high-voltage d-c test set is available.

Reference

1. Alternating and Direct Voltage Endurance Studies on Mica Insulation for Electric Machinery, **Graham Lee Moses**. *AIEE Transactions*, vol. 70, pt. I, 1951, pp. 763-69. (Ratio 1.6 recommended.)

H. F. Abbott (Quebec Hydro-Electric Commission, Montreal, Que., Canada): The extent to which the authors have covered the subject of the paper, in the length permitted, is worthy of tribute. However, I have a few questions to ask, and statements to question.

Bearing Clearances Relative to Runout

It seems general to provide as much as 20 mils of diametral clearance for guide bearings on large generators; yet we are concerned if the machine operates with 5 thousandths shaft throw. When there is 5 thousandths shaft throw, the oil film thickness, instead of being 10 thousandths uniformly around the shaft, is momentarily $7^1/_2$ mils on one side and $12^1/_2$ mils on the other side. It would appear that the reaction exerted by an oil film as thick as $7^1/_2$ must be very small; moreover, the difference in reaction created by the oil film on one side, being such a small percentage different than on the other side, cannot provide any considerable balancing force.

Is it not true, therefore, that normally the guide bearings provide little restraint against shaft throw? Is it not the case that when a machine shaft runs smoothly without appreciable throw, that it is either because eccentric forces—centrifugal, mechanical, hydraulic side thrust, and electromagnetic—have been reduced to near zero and the throwout is independent of guide bearing restraint, or because an unbalanced electromagnetic force from the stator or hydraulic force on the turbine holds the shaft towards one side of the guide bearings so that the necessary restraint is developed to result in little throw to the shaft?

Tolerances

Our experience has been that machining tolerances are usually much greater than those indicated in the paper. We would also point out that it is difficult to measure ± 5 mils on a 40-foot diameter stator bore.

Balancing

I would like to inquire why the trial weight should be placed at random after the high spot is known? Why not opposite the high point to avoid the angular relation of vectors? Also should not the dynamic balance be checked at two widely separated speeds to confirm whether the counterweight is the right distance from the center to give true dynamic balance at all speeds including the overspeed condition?

Dryout

I would like to see the statement "temperature should be brought up gradually," qualified approximately by specific figures. The period allowed for raising temperature varies widely between manufacturers.

On the final overpotential test we do not agree that direct current is acceptable. We believe that, if the AIEE standard is revised to include direct current some further qualification would have to be coupled to the d-c test such as leakage current, or shape of the curve of leakage current versus voltage under a specified rate of build-up. We have had instances where new generators did not come near to passing the standard a-c high-potential test and they had to be completely reinsulated, although a previous d-c test, which we had been urged to accept had been carried out successfully.

Ventilaton

I would suggest that particular stress be placed on the improved distribution in the air circulation improvements made in recent years.

F. L. Lawton (Aluminium Laboratories Ltd., Montreal, Que., Canada): The authors are to be congratulated on a distinct contribution to the literature on fabrication and erection aspects of vertical hydroelectric generators. The literature is, in fact, notably lacking and hence the paper is most welcome. It is to be hoped other manufacturers will contribute papers of this type in the future, as it will then become possible to place the erection of vertical water-wheel generators on that sound engineering basis so essential to optimum performance over a long service life.

The information given in the paper on dimensional tolerances is valuable. The authors make the statement "It is essential however that the final clearance be less than 10 mils to prevent vibration of the coil in the slot." It would be most helpful if the authors would indicate, to the extent information is available, the effect of limiting such clearance to, say, 5 mils.

Referring to the rotor rim, the statement is made that "The amount of interference is such that at moderate overspeed the rim remains tight on the spider, but at maximum overspeed the centrifugal forces overcome the interference forces." Do the authors know of cases where the rim has moved on the spider?

The use of strain gauges permanently located in the jack screws of the thrust bearing is a distinct step forward, as it should enable the determination of hydraulic thrust caused by the turbine runner more easily than has been the case in the past.

The authors state "Preliminary shaft alignment is carried out by adjustment of bearing jack screws until the coupling flanges are parallel within 0.15 mil and the flanges are in the same vertical plane." Should this not be horizontal plane? Are the dimensional tolerances for shaft runout at the coupling flanges and for out-of-parallelism between coupling flanges maximum values or do some customers specify closer tolerances?

What is the authors' experience as to the most effective way of minimizing adjustments after units have been installed for a few years when, in some cases, it is found that there has been a drop in elevation or settlement of the powerhouse structure on the downstream side?

K. R. Knights (The Hydro-Electric Power Commission of Ontario, Toronto, Ont., Canada): This paper is written on a subject that is of widespread interest. We are most interested in those machine tolerances that directly affect the results of the rotational alignment erection test. Our standard field alignment tolerance, as given in the following is not more stringent than that specified in the paper except that it provides limits on the coupled generator and turbine shafts: "The overall field alignment of the coupled generator and turbine shafts as determined from a rotational test—shall be such that the centre of each or either shaft shall not deviate from the true theoretical axis more than 0.00025 inch multiplied by the distance in feet from the thrust bearing rubbing surface to the point of measurement. In addition, the true theoretical axis of the coupled shaft shall not deviate from the plumb more than an amount calculated in the same manner."

To ensure that the foregoing alignment requirements are obtained with a minimum of field delay and for other reasons, it has been found desirable to have the thrust collar provide a light interference fit on the shaft, as noted in the paper, and to have the upper and lower surfaces of the thrust collar and runner plate faced true to the bore (shall not have a rotational error as measured by a dial indicator) within a tolerance such that the cumulative error of the two surfaces shall not exceed 0.001 inch. The shaft runout and the shaft coupling contact face are also held to acceptable tolerances for this purpose.

Jack screw strain gauges have been found to provide an accurate means of distributing the load between shoes. In addition, they have been utilized to make direct measurements of hydraulic thrust. Use of these gauges is much facilitated if the leads are extended down from the upper bracket. Design of the machine, however, should permit use of the "slugging arc" method of alignment so as not to be entirely dependent on devices for this important operation; a few strain gauges have failed in service.

The practice of accurately forming coils during manufacture so as to eliminate undue strain when tying and connecting them in place is considered to be in the interest of the purchaser. It is felt that coil insulation should only be disturbed where absolutely essential, as in the closing of splits.

Thermalastic insulated windings with full coils now have been purchased for a number of large, medium-speed water-wheel generators. As noted in the paper, the splits were closed successfully by lifting approximately six times the number of coils in a throw, in view of the comparative rigidity of this type of insulation.

It is stated in the paper that the upper bracket is mounted temporarily on the stator before a lift is made. On an umbrella machine, with a light upper bracket, the question arises as to what provision is made for lifting a complete stator.

Large, single guide bearing generators have always been purchased with the following stipulation, which is meant to provide assurance of entirely stable operation under all conditions of operation and test: "The design of the generator shall be such that it will have adequate mechanical stability to operate successfully under all overspeed and fault conditions which may be experienced during operation. This requirement shall apply with the generator either coupled to or uncoupled from the turbine."

With respect to the authors' comments on stator lamination insulating material, it would be of interest to hear their views on the relative merits of sodium silicate and high temperature baked on enamel from all viewpoints, particularly with respect to moisture resistance.

Our Kingsbury thrust bearings of the original Kingsbury design have a good operating record on our system. A number of machines supplied within a recent 2-year period, however, were equipped with shoes of the thick slab type and experience with this major variation from the original Kingsbury design has not been so successful. As a result of this experience, we are in agreement with the present practice of not only eliminating the babbit bond as noted in the paper but also supplying all shoes along the lines of the original undercut design.

W. D. Houser, W. Hindle, and **J. A. Tyerman:** The authors wish to thank the several discussers of this paper and take this opportunity for replying to some of the points raised.

The advantages of sodium silicate or water glass over baked-on enamel or varnish as an insulation on stator laminations are that it: 1. has a thinner film for equal insulation which enhances a better stacking factor; 2. has a slower rate of deterioration; 3. is more resilient; 4. withstands higher temperature such as might occur in a stator fire; and 5. withstands higher stacking pressures as it is an inorganic inert material.

Some manufacturers are known to design rims that are loose at all speeds but are suitably restrained so that only uniform radial expansion is allowed.

We agree with Mr. Duffy that elaboration on the use of strain gauges for thrust bearing adjustment would be of interest to operating personnel, and it could well be the subject of a further paper. When reassembling a machine after overhaul, no adjustment is required if the old shoes are reused. Minor adjustment is sometimes required with new shoes because of slight manufacturing tolerances between individual shoes. With regard to strain gauge failures, we have found that improvements in the termination of the leads from the load cell have reduced the number of failures to a very low percentage. Further improvements can be expected to reduce this almost to the vanishing point.

In the case of installations that have suffered foundation settlement, shaft misalignment can usually be compensated for by adjustment of the guide and thrust bearings as they are both of the pivoted type. The settlement would have to be very severe before it would require a releveling of the stator frame.

To clear up any misunderstanding over the tolerance given in the paper for stator bore, we would like to make it clear that this refers only to the bore of the frame itself. We agree that it is not possible to hold the bore of the stacked core to tolerances of ± 0.005 inch in diameter. The gauges used for measurement of large bores to the accuracies indicated are quite practical and are in daily use in our shops. The dimensional tolerances given in the paper are actually closer than that required by any known purchase specification to date and are giving satisfactory results in the field.

In designing the coil and slot sizes, the designer chooses dimensions that will result on the average in 15-mil clearance. With side mica strips available in 10-, 15-, 20-, and 25-mil thicknesses, it is possible to achieve a final clearance of not greater than 10 mils and averaging 5 mils. A small clearance is considered necessary to prevent tape migration caused by the thermal movement of the copper conductors, which can occur when the tape is prevented from moving with the copper.

Direct voltage testing has been extensively used by our field erectors for several years now, using up-to-date d-c to a-c ratios as developed by the AIEE subcommittee studying this subject. While we have had very few occasions to doubt the validity of such d-c testing, we do feel that the higher ratio now recommended by the subcommittee is a step in the right direction.

For asphalt and earlier types of coils, it is highly desirable to drive out contained moisture and solvents very slowly to avoid mechanical damage from vapour pressures. In general, the stator temperature for dryout is brought up to 80 degrees centigrade at a uniform rate over a 24-hour period.

We agree with Mr. Abbott that an oil film of 10-mil thickness will do little to restrain a shaft throw of 5 mils, but it must be realized that the clearance will be less than 10 mils at operating temperatures. However we feel that shaft throw does not originate in the guide bearing, and any serious throw should be overcome at the source, if possible, rather than call upon the guide bearing to restrain it. Guide bearings to restrain any considerable radial forces would then have to be much bulkier and more expensive than those commonly in use today.

Dynamic balancing of vertical water-wheel generators is of considerable importance and a complete explanation is too lengthy for this paper. It too could well be the subject of a separate paper.